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EFFECTIVENESS OF PILOT CAR OPERATIONS IN REDUCING SPEEDS IN A LONG-TERM RURAL HIGHWAY WORK ZONE

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ABSTRACT

Pilot cars are used in one-lane two-way work zones to guide traffic and keep their speeds within posted limits. While many studies have examined the effectiveness of measures to reduce vehicle speeds in work zones, little is known about the reductions achievable through the use of pilot cars. This paper examines the effectiveness of a pilot car in reducing travel speeds in a rural highway work zone in Queensland, Australia. Analysis of speed data covering a period of five days showed that a pilot car reduced average speeds at the treatment location, but not downstream. The proportion of vehicles speeding through the activity area was also reduced, particularly those traveling at 10 km/h or more above the posted limit. Motorists were more likely to speed during the day, under a 40 km/h limit, when traffic volumes were higher and when there were fewer vehicles in the traffic stream. Medium vehicles were less likely to speed in the presence of a pilot car than light vehicles. To maximize these benefits, it is necessary to ensure that the pilot car itself is not speeding.

Keywords: Work zone safety, roadwork safety, pilot car, pilot vehicle, speeding, speed reduction.

INTRODUCTION

Noncompliance with posted speed limits in work zones has been identified as a serious safety concern worldwide (e.g., *1-8*). Research in Victoria, Australia, found that more than 40% of cars and more than 70% of trucks exceeded signed speed limits in work zones (*9*). Over 60% of drivers exceeded the posted 60 km/h speed limit in another Victorian study (*10*), and 10% and 1% of drivers exceeded the limit by at least 15 km/h and 30 km/h respectively. Consistent with these statistics, a state-wide survey of truck drivers in Illinois (*11*) found that half of the respondents admitted to exceeding work zone speed limits despite 90% considering that work zones were more hazardous than regular road sections. Drivers are likely to drive at speeds they perceive to be suitable, or with which they are comfortable, regardless of the posted limits (*9, 12*). As the lowest speeds are usually observed in the active work area (*13*), speeding behavior depends somewhat on the actual work activities occurring (or perceived to be occurring) in different sections of a work zone.

A wide range of measures are used to reduce speeding in work zones and their effectiveness has been the subject of considerable research. In a recent review of this literature, Debnath et al. (*14*) classified the measures into four categories: informational, physical, enforcement, and educational measures. Among the informational measures, static speed limit signs were found to generally reduce speeds but did not bring speeds down to posted limits (*9, 15, 16*). Advance warning signage was found to have no effect on speeds (*10, 17*), but variable message signage (VMS) (*1, 2, 12, 18*) and VMS with speed feedback (*19, 20*) reduced speeds significantly. Driver warning systems (e.g., in-vehicle visual and audio warnings, emergency flasher traffic control device) were also found to improve drivers' compliance with speed limits (*21-23*). Studies examining physical measures, such as rumble strips (*7, 24-26*) and optical speed bars (*27*) produced inconsistent findings, but these measures appeared to have relatively small effects on speeds and were ineffective for transient and moving work zones. Enforcement was found to be the most effective of all measures. The presence of speed cameras (*17, 28-30*) and police cars with flashing lights (*4, 17, 30*) in work zones significantly improved speed limit compliance, although the effects were often temporary and localized. Imposing higher fines for violating speed limits in work zones appeared to have little effect on speeds (*31, 32*). Formal evaluations of educational measures are lacking in the literature, but many (e.g., *4, 9, 31*) have argued that educational and awareness campaigns are likely to be effective when used in conjunction with enforcement initiatives.

Despite the many studies evaluating the effectiveness of speed control measures in work zones, pilot car operation has not yet been examined. Use of pilot cars is among the methods prescribed in the FHWA's Manual on Uniform Traffic Control Devices (MUTCD) (*33*) to coordinate one-way movements in work zones when a single lane is open to two-way traffic. Similarly, the MUTCD used in Queensland, Australia (*34*) states that pilot cars (a.k.a. 'pilot vehicles' in Queensland) are required to guide traffic through static work zones when a) part of the work zone is out of view of the supervisor/traffic controller, b) the posted speed limit is less than 40 km/h due to the presence of hazards to workers, c) speed is required to be kept low to minimize damage to works, or d) the travel path is not obvious to follow. In addition to these requirements, a pilot car must carry a vehicle mounted warning device (a single/pair of yellow beacon lamps or an illuminated flashing arrow sign) and traffic should be instructed, either verbally or by means of signage, to follow and not to overtake the pilot car.

The emergency flasher traffic control device (EFTCD) evaluated by Bai and Li (*22*) is the safety measure most similar to a pilot car in terms of operational characteristics. However, the use of an EFTCD differs significantly from the use of a pilot car. EFTCDs are used by drivers of public vehicles, whereas a pilot car is driven by a trained operator who has prior and proper knowledge about the work zone. Moreover, a public vehicle equipped with EFTCD may choose not to drive within posted speed limit, but a pilot car is used to keep motorists' speeds within posted limits or at a safe level. In an older study, Burritt and Guenther (*35*) used two pilot cars (one at the beginning of the traffic queue and the other at the end) to develop a relationship between approach volume and maximum service flow rate. However, there were no quantitative comparisons between the presence and absence of pilot car operation, or examinations of the speed reduction effects of the pilot cars. As this gap in the literature suggests, the effectiveness of pilot cars in reducing travel speeds is not well understood.

This paper aims to examine the effectiveness of pilot car operation in a long-term one-lane two-way work zone. To achieve this objective, travel speeds for five consecutive days at a work zone situated on a normally two-lane, two-way rural highway in the state of Queensland, Australia were analyzed. Analyses focused on examining the speed reduction effects of pilot car operation within the work zone, as well as at a downstream location for halo effects. The study method, including the data collection process and analysis techniques, is presented in the following section, followed by presentation of the results and discussion of the findings, before finally concluding the paper.

METHOD

Experimental Setting

This study was conducted in a long-term 4.1 km work zone on a rural highway (Bruce Highway), which is the major transport route servicing north-eastern Australia. Work was conducted over seven months, with data collection commencing about five months into this period and two months before project completion. The highway at this point is a sealed one lane each way undivided road with pre-work zone speed limits of 100 km/h at the southern end and 80 km/h at the northern end. This stretch of road is straight and mostly flat with good sight distance. A schematic diagram of the work zone showing the posted signage and the location of speed measurement points is presented in Figure 1. It should be noted that the typical components of a work zone in Queensland's MUTCD (*34*) are termed differently from the FHWA's MUTCD (*33*). For example, the terms 'taper area', 'safety buffer', and 'work area' in Queensland correspond to the FHWA's terms 'transition area', 'buffer space', and 'work space' respectively. The terms 'advance warning area' and 'termination area' are similar in both versions of the MUTCDs. The term 'activity area' is used in (*33*) to represent the work space and buffer space together; however, a similar term is not used in (*34*).

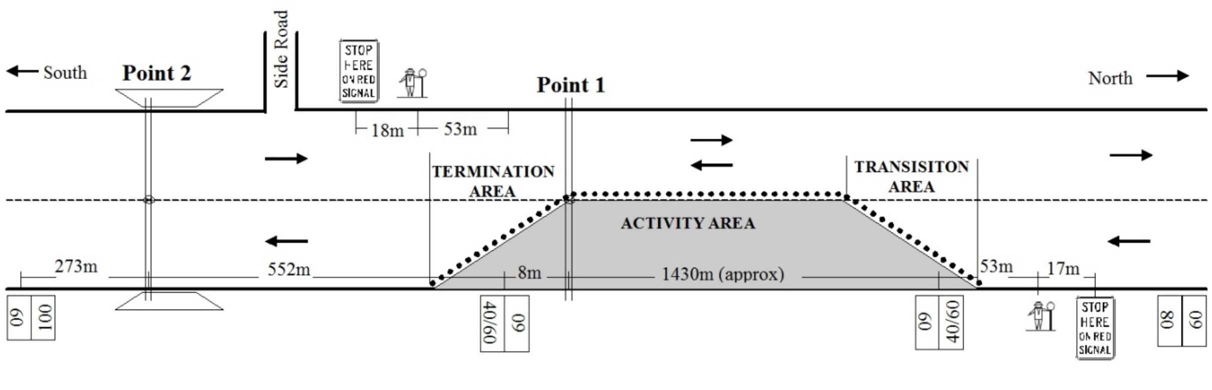

FIGURE 1 Plan of work zone.

Work involved full closure of one lane within the activity area for the purpose of resurfacing, with the closed lane alternating as required. The direction of traffic was alternated by manual traffic control with temporary traffic lights. Standard sets of signage following the MUTCD used in Queensland (*34*) were placed at both ends of the work zone starting with 'Road Work Ahead/Reduce Speed/80km/h' followed by 'Reduce Speed/60km/h', and 'Prepare to Stop/Do Not Overtake' signs at respective 300 meter intervals. A 'Standard roadworker sign' coupled with 'Reduce Speed/40km/h' was placed at both ends of the transition and termination areas with repeated signs at every 300 meters within the activity area. South-bound traffic was stopped at the northern end of the work zone 44 meters before the start of the transition area by a traffic controller using portable traffic lights. Another traffic controller with a stop/slow bat was placed at an upstream location to prevent vehicles from queuing on a bridge located near the work zone. Using similar methods, the north-bound traffic was stopped 42 meters before the start of the termination area at the other end of the work zone.

A pilot car (Figure 2) was used to control the speed of public vehicles through the closed lane section of the work zone during the daytime working hours (generally 0600-1800 hours). The pilot car carried windscreen-mounted and side-mounted flashing amber lights, and a top-mounted VMS displaying alternating amber lights to the rear. The pilot car guided traffic within the transition area and the termination area only. Traffic controllers at both ends used radios to inform each other about the last public vehicle in the queue (usually by its color, make, and/or model).

FIGURE 2 Pilot car in operation.

Speed data for the south-bound traffic were collected at two points: at the activity area in the southern end of the work zone (Point 1) and at a location 560 meters downstream of the first point (Point 2). Distances of Point 1 from the locations where traffic was stopped at the southern end (1500 meters) and northern end (79 meters) of the work zone suggests that the north-bound traffic (including the pilot car) might not have reached at their desired speeds of travel when crossing the tubes at Point 1 starting from a complete stop at traffic control. On the other hand, the large distance for the southbound traffic would allow the pilot car to reach its desired speed of travel at Point 1. Therefore, the focus of the study is limited to the south-bound traffic only.

Speed data from both lanes were collected using pairs of pneumatic tubes installed 1 meter apart on the pavement and connected to Metrocount Vehicle Classification System. Data for five consecutive days (Wednesday 0845 hours to Sunday 2400 hours) was analyzed. The pilot car was present during the daytime hours of Thursday to Saturday. Workers were present in the closed lane and on the shoulder from Wednesday to Saturday during the daytime hours when the posted speed limit was 40 km/h in the activity area (the limit was 60 km/h during the night hours). Wet surface due to rain precluded work on Sunday and a 60 km/h speed limit was posted throughout the day and night hours. The posted speed limit at Point 2 was 60 km/h for the entire data collection period.

Data

Speed, headway, gap, type of vehicle, and time were collected for each vehicle which passed over the tubes. Vehicles were classified using the ARX vehicle classification scheme, which classifies vehicles into three aggregate classes: Light vehicles (Very short – bicycle, motorcycle; Short – sedan, wagon, 4WD, utility, light van; Short towing – trailer, caravan, boat etc.), Medium vehicles (two and three axle bus or truck, four axle truck), and Heavy vehicles (articulated vehicle or rigid vehicle and trailer with more than two axles, B-double or heavy truck and trailer, double or triple road train or heavy truck and more than one trailer). Data was collected and analyzed in Metric units (e.g., speed in km/h, gap in meters).

Individual vehicle data were extracted by running ‘Individual vehicle reports’ from the Metrocount software. Separate datasets were obtained for the two data collection points. A rigorous data cleaning process was then undertaken to identify and remove the data points which might be erroneous. Firstly, the data points with zero headway, which were reflected in the individual vehicle reports with the label “coerced sequence”, were removed from the datasets. About 8.5% (n =1493 out of 17659) and 0.22% (n = 37 out of 16957) of the data points were removed at Point 1 and 2, respectively. Secondly, the observations where a vehicle was heading north were removed to obtain only the south-bound observations. Finally, observations of pilot car and work vehicles (where identifiable) were separated from the public vehicle observations in the Point 1 dataset. A pilot car is usually the first vehicle in a traffic queue, with exception in some cases where a work vehicle was ahead of the pilot car. Such cases and the exceptions were identified by examining the types of vehicles (a pilot car is a light vehicle) and headways of successive vehicles. For instance, if two vehicles at the front of a queue have large headways and the third vehicle has small headway, it is likely that the second vehicle is the pilot car and the first one is a work vehicle. It should be noted that Point 2 was away from the pilot car operation area; therefore, separation of such data was not required for Point 2. The final datasets after the cleaning exercise included 15,285 and 16,618 observations for Point 1 and Point 2, respectively.

Statistical Analyses

The datasets were analyzed using a three-step approach. In the first stage, the Point 1 data were analyzed descriptively to calculate the differences in mean speeds and proportion of speeding vehicles when a pilot car was in operation and when it was not. Effects of the pilot car on speed reduction for different types of vehicles were also examined. Since the posted speed limit during pilot car operation was 40 km/h, only the observations under the same limit are included in this stage of the analysis.

While this stage provides a quick and direct comparison of speeds in the presence and absence of the pilot car, it is important to note that motorists' speeds do not necessarily depend only on the presence of the pilot car: characteristics of the work zone and traffic are likely to affect the speeds as well. Therefore, in the second stage, a regression model was developed to model the probability of a public vehicle speeding in order to examine how presence of the pilot car and other characteristics of the work zone and traffic affect this probability. The two categories of a public vehicle's speed (speeding or not speeding) can be well formulated as a binary logistic model by using the binary outcomes speeding (= 1) and not-speeding (= 0) as the response variable. A set of explanatory variables describing the characteristics of the work zone and traffic (see Table 2) which were assumed to be associated with the probabilities of public vehicles travelling above the posted speed limits were included in the model. To estimate the parameters, the model was fitted using the 15,285 observations of Point 1. The third stage involved examining the downstream effects of pilot car operation by comparing mean speeds and proportions of speeding vehicles at Point 2 under the conditions of presence and absence of the pilot car in the upstream activity area. The pilot car was present only during the day (0600-1800 hours) but the speed limit was 60 km/h at Point 2 during both day and night. Therefore, the downstream effects were analyzed separately for day and night periods to examine if the patterns differ.

RESULTS

Effects of Pilot Car in Activity Area

The speed profile of all vehicles (average speeds in 15 minute intervals) at the activity area in the work zone along with posted speed limits are shown in Figure 3. All days except the last day of data collection had posted limits of 40 km/h during the daytime hours (0600-1800) and 60 km/h during the night-time hours (1800-0600). The last day of data collection, when no work was undertaken because of the wet surface, had a 60 km/h limit for both day and night-time hours. The speed profile of the remaining days shows that the average speeds were generally above the posted limit during the daytime hours, but were under the limit during the night-time hours. This indicates that there is higher prevalence of speeding in daytime than at night. On the last day, average speeds were around the posted limit, but dropped significantly during the morning hours, possibly because of rainfall in the morning. All of the 15 minute blocks had some speed observations except one, which had zero average speed.

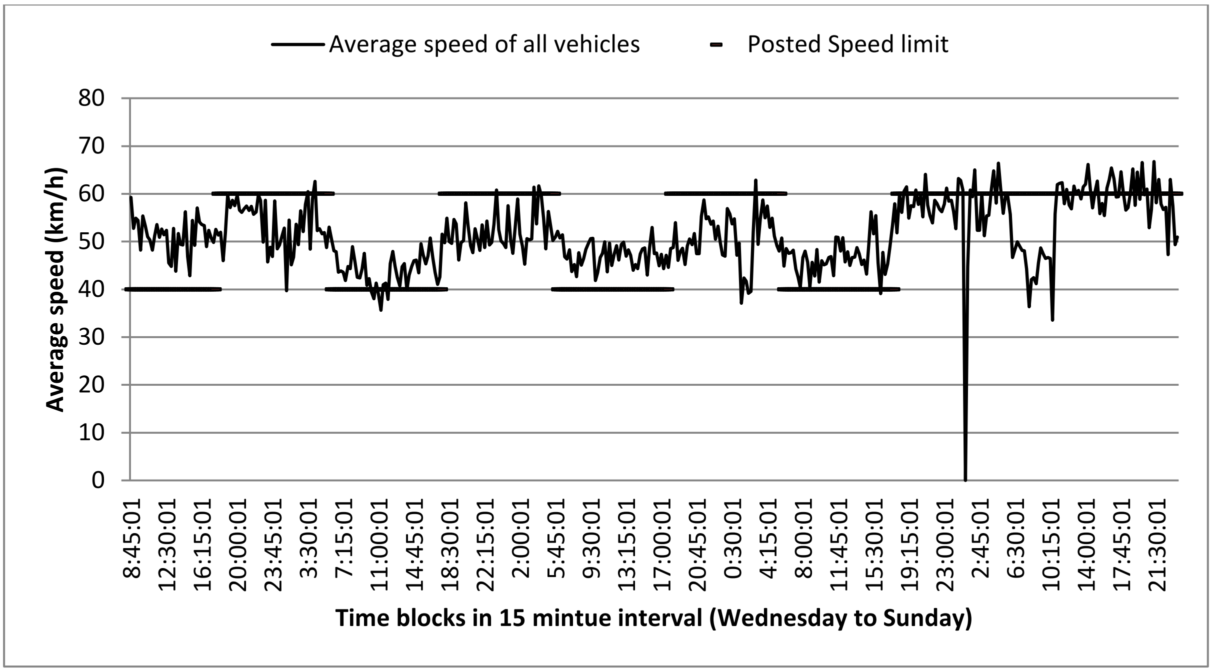

FIGURE 3 Average speed profile of all vehicles in 15 minute intervals.

TABLE 1 Effects of Pilot Car in Activity Area

	Pilot car present											
	No				Yes				Reduction (No - Yes)			
Type of vehicle (No of obs.)	All (2271)	Light (1675)	Medium (265)	Heavy (331)	All (7977)	Light (6107)	Medium (834)	Heavy (1036)	All	Light	Medium	Heavy
Mean speed (km/h)	52.03	52.12	51.35	52.11	46.13	46.22	45.28	46.33	5.90	5.90	6.07	5.78
Standard Dev. of mean speed	6.23	6.25	6.69	5.67	5.84	5.79	6.13	5.86	NA	NA	NA	NA
% vehicle speeding	97.75	98.03	95.09	98.49	85.27	85.90	80.10	85.71	12.48	12.13	15.00	12.78
% vehicle speeding by 5 km/h	88.46	88.42	85.28	91.24	55.72	56.31	49.28	57.43	32.74	32.11	36.00	33.81
% vehicle speeding by 10 km/h	62.92	62.81	61.89	64.35	24.78	24.94	21.46	26.54	38.14	37.87	40.42	37.81
% vehicle speeding by 15 km/h	30.74	31.46	27.92	29.31	7.58	7.61	6.71	8.11	23.15	23.85	21.21	21.20
% vehicle speeding by 20 km/h	9.82	10.21	8.30	9.06	1.24	1.16	1.56	1.45	8.58	9.05	6.74	7.62

Table 1 presents the mean speeds and proportions of vehicles speeding with and without pilot car operation in the activity area (Point 1), both aggregately and separately for different types of vehicles. The mean speed of all vehicles under a posted speed limit of 40 km/h was 5.9 km/h lower (dropped from 52.0 to 46.1 km/h) when a pilot car was present. The size of the reduction did not differ significantly by type of vehicle. Despite these reductions, the mean speed of all vehicles remained 6.1 km/h above the posted limit when the pilot car was in operation.

Under pilot car operation, the proportion of vehicles travelling above the posted limit fell by 12.5%. Almost all vehicles (97.8%) violated the posted limit in the absence of the pilot car, whereas 85.3% did so when it was present. The largest reduction in prevalence of speeding was seen for medium vehicles (15.0%), followed by heavy (12.8%) and light vehicles (12.1%). The effect of the pilot car in reducing speeding vehicles was greater (32.7%) in the case of travelling at least 5 km/h above the posted limit. Similar patterns of reductions were seen for the three types of vehicles. Despite these reductions, 55.7% vehicles (again with a smaller share of medium vehicles than the other types of vehicles) still travelled at least 5 km/h above the limit.

The greatest reduction occurred in the proportion of vehicles travelling at least 10 km/h over the limit (38.1%) with a greater reduction for medium vehicles (40.4%) than the light (37.9%) and heavy vehicles (37.8%). For the three cases (proportion of vehicles speeding, speeding by 5km/h, and speeding by 10 km/h), operation of the pilot car had the greatest effect on medium vehicles. However, in the case of travelling at more than 15 km/h above the posted limit, operation of the pilot car had more effects on light vehicles in reducing the proportion of speeding vehicles than on medium and heavy vehicles.

It is important to know the speed profile of the pilot car in order to evaluate its speed reduction ability. In a total of 162 trips made by the pilot car during the study period, it travelled at a mean speed of 38.1 km/h (S.D. = 4.6). It exceeded the posted 40 km/h limit on 34% of its trips, and exceeded the limit by 5 km/h or more on 7.4% of the trips.

Regression Model Results

To model the probability of a public vehicle speeding in the work zone under pilot car operation, it is necessary to define the response variable according to the speed pattern of the pilot car. This is because the pilot car set the highest possible speed for the vehicles following it. Therefore, to account for occasions when the pilot car travelled above the limit and to keep a buffer above the posted limit, the response variable of the regression model is defined as 'a public vehicle speeding at least by 5 km/h' (= 1) and 'not-speeding' (= 0).

The parameters of the binary logistic model were derived using the maximum likelihood estimation method in the software STATA 11.2. The parameter estimates, odds ratios (O.R.), and their statistical significance are presented in Table 2. The fitted model produced an Akaike Information Criteria (AIC) value of 14985 and likelihood ratio statistics of 6101.2 (19 *df*), which is well above the corresponding critical value for significance at the 1% level, implying that the model has sufficient explanatory power. The estimation results of significant variables are discussed in the following paragraph.

A public vehicle is more likely to travel at 5 km/h or more above the posted speed limit (40 km/h) during daytime hours (6am-9am, O.R. = 1.20; 12pm-3pm, O.R. = 1.17; and 3pm-6pm, O.R. = 1.17) and less likely during the evening and night hours (6pm-9pm, O.R. = 0.56 and 3am-6am, O.R. = 0.64) relative to the 9am-12pm period. The estimates for the hours between 9pm-3am were not statistically significant. The odds of speeding were 37.9% higher when workers were not present and were 53.7% lower when workers were having a break. Vehicles were more likely to speed when the posted limit was 40 km/h (O.R. = 91.13) than when it was 60 km/h. Presence of the pilot car was associated with 85.4% lower odds of a vehicle speeding. In comparison to light vehicles, medium vehicles were less likely to speed (22.3% lower odds), but the result for heavy vehicles was not statistically significant. The likelihood of vehicles speeding was found to increase with increasing traffic volume (O.R. = 1.01) and to decrease with an increase in the proportion of medium and heavy vehicles (O.R. = 0.98). Both of these variables were defined in 15 minute blocks around the time when the vehicle's speed was measured. Relative to the vehicles with a small gap to the vehicles in front (<= 2 seconds), vehicles with higher gaps were more likely to speed. The odds of a vehicle speeding were 24.7% higher when the gap was 2.1 to 4 seconds, 83.3% higher when the gap was 4.1 to 8 seconds, and 94.6 % higher when the gap was greater than 14 seconds. The highest odds (210.7% higher than the case of <= 2 seconds gap) were found for vehicles with gaps of 8.1 to 14 seconds.

TABLE 2 Explanatory Variables and Regression Estimates

Explanatory variable	**Description**	**Beta**	**O.R.**	**p value**
Time of day				
00:01 - 03:00	If yes = 1, otherwise = 0	-0.338	0.713	0.257
03:01 - 06:00	If yes = 1, otherwise = 0	-0.453	0.636	0.018
06:01 - 09:00	If yes = 1, otherwise = 0	0.186	1.204	0.007
09:01 - 12:00*	If yes = 1, otherwise = 0			
12:01 - 15:00	If yes = 1, otherwise = 0	0.159	1.172	0.004
15:01 - 18:00	If yes = 1, otherwise = 0	0.160	1.174	0.009
18:01 - 21:00	If yes = 1, otherwise = 0	-0.576	0.562	<0.001
21:01 - 24:00	If yes = 1, otherwise = 0	0.095	1.100	0.618
Presence of workers in work zone				
No	If yes = 1, otherwise = 0	0.321	1.379	0.001
Yes*	If yes = 1, otherwise = 0			
Work break	If yes = 1, otherwise = 0	-0.770	0.463	<0.001
Posted speed limit	If 40 km/h = 1, 60 km/h = 0	4.512	91.132	<0.001
Presence of Pilot Car	If yes = 1, otherwise = 0	-1.921	0.146	<0.001
Type of vehicle				
Light vehicle*	If MC, SV, or SVT = 1, otherwise = 0			
Medium vehicle	If TB2, TB3, or T4 = 1 , otherwise = 0	-0.252	0.777	<0.001
Heavy vehicle	If ART3, ART4, ART5, ART6, BD, or DRT = 1 , otherwise = 0	-0.084	0.920	0.189
Traffic volume^	Number of vehicles in traffic stream	0.009	1.009	<0.001
Proportion of large vehicles^	% of medium and heavy vehicles	-0.018	0.983	<0.001
Gap (from front vehicle) in meters				
<=2 seconds*	If gap <=2 secs = 1, otherwise = 0			
2.1 - 4 seconds	If gap 2.1-4 secs = 1, otherwise = 0	0.221	1.247	<0.001
4.1 - 8 seconds	If gap 4.1-8 secs = 1, otherwise = 0	0.606	1.833	<0.001
8.1 - 14 seconds	If gap 8.1-14 secs = 1, otherwise = 0	1.134	3.107	<0.001
>14 seconds	If gap >14 secs = 1, otherwise = 0	0.666	1.946	<0.001
Summary statistics				
Number of observations		15285		
Log-likelihood (at zero)		-10523.09		
Log-likelihood (model)		-7515.55		
AIC		15071.1		
G^2		6015.08	(19 *df*)	<0.001

* Reference category; ^ measured in 15 minute block around the time when a vehicle's speed is measured

TABLE 3 Downstream Effects of Pilot Car

Type of vehicle	Time	Pilot car present	No of obs.	Mean speed (km/h)	% vehicles speeding	% vehicles speeding by 5 km/h	% vehicles speeding by 10 km/h	% vehicles speeding by 15 km/h	% vehicles speeding by 20 km/h
All vehicles	Day	Yes	8557	61.59	62.05	31.23	11.15	2.89	0.88
		No	4886	62.29	62.73	36.45	17.58	8.33	4.20
		No-Yes		0.70	0.68	5.23	6.43	5.44	3.32
	Night	No	3175	71.56	91.69	77.67	54.71	32.38	17.01
Light vehicles	Day	Yes	6738	61.88	62.67	31.92	11.74	3.12	0.95
		No	3915	62.7	64.55	37.65	17.47	7.84	3.75
		No-Yes		0.82	1.87	5.73	5.73	4.72	2.80
	Night	No	2186	71.38	92.09	77.04	53.93	31.24	15.46
Medium vehicles	Day	Yes	573	59.79	57.24	26.70	9.08	1.57	0.35
		No	359	59.7	52.92	27.30	15.60	10.31	5.85
		No-Yes		-0.09	-4.32	0.60	6.52	8.74	5.50
	Night	No	184	72.26	89.67	76.09	60.87	38.59	24.46
Heavy vehicles	Day	Yes	1246	60.83	60.91	29.53	8.91	2.25	0.72
		No	612	61.17	56.86	34.15	19.44	10.29	6.05
		No-Yes		0.34	-4.05	4.62	10.54	8.05	5.32
	Night	No	805	71.91	91.06	79.75	55.40	34.04	19.50

Downstream Effects

Table 3 summarizes the effects of the pilot car at a downstream location (Point 2), both aggregately and separately for different types of vehicles. The mean speeds during daytime with and without pilot car operation were similar, suggesting that the pilot car had no significant effects on downstream speeds. However, the night-time speeds (when the pilot car was not present) were higher than the day speeds in the presence of the pilot car.

During daytime at Point 2, the proportion of light vehicles travelling above the posted limit was 1.9% lower when the pilot car was in operation compared with when it was not. On the other hand, the prevalence of speeding increased by 4.3% and 4.1% for medium and heavy vehicles respectively. However, these increases were not reflected in trends for travel at a significantly higher level above the speed limit. When the proportions of vehicles speeding by at least 5 km/h or more above the limit were compared, none showed evidence of increase. The greatest reduction for medium vehicles was observed in the case of vehicles speeding by at least 15 km/h above the limit (8.7%), followed by when vehicles were speeding by at least 10 km/h above the limit (6.5%). For heavy vehicles, the highest reductions were for vehicles speeding by at least 10 km/h (10.5%) and by at least 15 km/h (8.1%). For light vehicles, greater effects were observed for smaller margins above the limit than in the cases of medium and heavy vehicles. Both the cases where vehicles were speeding by at least 5 km/h or 10 km/h saw a reduction of 5.7%.

DISCUSSION

In the activity area, the average speed of vehicles was reduced when a pilot car was present and the reductions were similar for different types of vehicles. However, the average speed remained about 6 km/h above the posted limit when the pilot car was present. These findings imply that the pilot car effectively reduced travel speeds when in operation, but did not necessarily confine the speeds to within the posted limit.

The effectiveness of the pilot car in bringing down speeds could have been restricted by the failure of the pilot car to always obey the posted speed limit. The pilot car exceeded the posted speed limit on one-third of its trips, and by 5 km/h on 7.4% of trips. Since a pilot car leads and guides the public traffic stream through the work zone, the maximum speeds of the public vehicles, particularly those which are in the traffic stream immediately behind the pilot car, will be influenced by the speed of the pilot car. When the pilot car travelled at a speed higher than the limit, the public vehicles following the pilot car were likely to travel at a similar speed. Therefore, the excess speeds of the pilot car above the limit arguably contributed to the 6 km/h excess in the mean speed of all vehicles. Furthermore, the excess speed could also be observed due to the higher speeds of the vehicles which joined the traffic stream with higher gaps between them and their leading vehicles. Results showed that vehicles with higher gaps have a greater likelihood of speeding since these vehicles have more opportunity and room to accelerate and catch the traffic stream immediately behind the pilot car. Therefore, it is reasonable to argue that a pilot car has more effect on the speeds of vehicles following it closely than on the speeds of those which are far behind the traffic stream.

In addition to reducing mean speeds, the presence of the pilot car also reduced the proportion of vehicles exceeding the posted speed limit. While in the absence of the pilot car almost all vehicles (98%) violated the speed limit, about 85% still did in its presence. The pilot car had a much larger effect on the proportions of vehicles exceeding the speed limit by 5 km/h or more or 10 km/h or more (33% and 38% reductions, respectively). Thus, the pilot car effectively reduced the number of vehicles travelling at particularly risky speeds.

While the pilot car significantly reduced speeding by all types of vehicles, there were larger reductions in the proportions of medium vehicles speeding by a margin of 5 km/h or 10 km/h or more. With regard to higher margins (15 or 20 km/h or more), however, the pilot car had larger effects on the light vehicles than on others.

Motorists were less likely to speed when the proportion of large vehicles (medium and heavy) in the traffic stream was greater. These large vehicles are generally slower than the light vehicles in accelerating from a stop position or a slow speed. Thus, the vehicles travelling behind these large ones had no option other than to follow the speeds of the large vehicles. Furthermore, results showed that the medium vehicles were less likely to speed compared to light vehicles (the result was non-significant though for heavy vehicles). Thus, both the lower likelihood of speeding and the slow acceleration of large vehicles might prevent light vehicles from speeding when there are higher proportions of large vehicles in a traffic stream.

Motorists were also more likely to speed when workers were not present in work zone. Generally, work was not conducted during the night-time hours. Pilot car operation was also dependent on the presence of workers on road. Results showed that the night-time hours were associated with less speeding than the daytime hours, while absence of the pilot car was associated with more speeding. This apparent contradiction warrants further investigation of the effects of pilot car operation on responses to the presence of workers.

Although presence of the pilot car influenced motorists' speeds in the activity area considerably, no significant halo effects were found at a location 560 meters downstream of the activity area. The comparison of average speeds during daytime hours when the pilot car was present with when it was not revealed no significant differences. However, the average speeds during night-time hours were higher than those of the daytime hours, although this difference may not necessarily relate directly to the status of the pilot car. It is possible that speeds at night are generally higher than during the day. A comparison of the average speeds on nights following a day with pilot-car operation with those following a day without pilot car operation revealed no significant difference (the average speed was only 0.52 km/h higher in the nights following a day without pilot car operation). Although the average speeds during daytime hours were unchanged, presence of the pilot car was associated with a reduction in the proportion of vehicles speeding by a margin of 5 km/h or more above the posted limit. Reductions in the proportions of vehicles speeding with a greater margin were generally higher for heavy vehicles than for other types of vehicles. This may imply that motorists, especially the heavy vehicle drivers who travel at speeds significantly higher than the posted limit, are more influenced by presence of a pilot car at an upstream location than those who travel at speeds close to the posted limit.

It would be interesting to compare the effects of a pilot car obtained in this study with those of other speed reduction measures. Unfortunately, many of the other measures have been studied in work zones with much higher speed limits (mostly 89 to 113 km/h). The 5.9 km/h mean speed reduction observed with the pilot car is similar to the 7.4 km/h speed reduction (under a speed limit of 105 km/h) and 5.8 km/h reduction (under a limit of 89 km/h) found for EFTCD by Bai and Li (*22*). A pilot car appears to have a greater effect on speeds than portable rumble strips or VMS without feedback in Fontaine et al.'s study (*19*). However, the speed reductions associated with pilot car operation were less than that reported for a speed feedback system (up to 16 km/h on two-lane roads with 113 km/h posted speed limit by Fontaine et al. (*19*)) or a speed camera (6.7-12.5 km/h reported by Hajbabaie et al. (*30*)) or police presence (17 km/h reported by Huebschman et al. (*17*)).

This study examined the effects of pilot car operation on speeds of public vehicles in a long-term large rural highway work zone, which had two lanes with only one open to traffic, in the State of Queensland, Australia. Since the study has not been repeated and the findings have not been validated in other similar work zones because of resource constraints, the results might be subject to various unknown work-zone-specific effects. Furthermore, whether the effects of a pilot car will be similar in short-term or urban work zones has not been tested. Thus, care should be taken in generalizing the results to smaller and short-term work zones, as well as to other parts of Australia and the world with different environmental and regulatory conditions. Further research should include generalizing the results by examining effectiveness of pilot car operation in multiple work zones and how its effectiveness varies with different geometric, traffic, and operational characteristics of work zones. Another important extension of this research would be examining the effects of pilot car operation on the queue and gap characteristics of public vehicles and whether pilot car operation influences the speed variability and the risk of rear-end crashes at the tail of traffic queues.

CONCLUSIONS

This paper evaluated the effectiveness of pilot car operation in reducing travel speeds in a long-term highway work zone. The analyses revealed that average travel speeds under pilot car operation reduced in the area where the pilot car operated, but not at a location downstream of this area. Even with the pilot car, the mean speed at the activity area remained about 6 km/h higher than the posted limit. Speeding by the pilot car may have contributed to this finding. In addition to the effect on mean speed, the presence of the pilot car also reduced the proportion of speeding vehicles. Similar reductions in mean speeds are observed for all types of vehicles; however, the reductions in proportions of speeding vehicles were not similar. The effect of pilot car operation in reducing the proportion of speeding vehicles by a small margin (less than 15 km/h above the limit) was greater for medium vehicles than for other types of vehicles. However, for a larger margin (15 km/h or more) above the limit, the greatest effect is seen for light vehicles. A public vehicle is more likely to speed during daytime hours when the posted limit is 40 km/h and traffic volume is higher than in night-time hours. Higher likelihood of speeding is also associated with higher gaps between vehicles. The pilot car seemed to have greater effect in reducing speeds of the vehicles following it closely in a traffic stream than those which are far behind the traffic stream. Higher proportions of medium and heavy vehicles in a traffic stream were associated with a lower likelihood of speeding. The greater likelihood of motorists speeding when workers are not present in work zone deserves further investigation. Given that the pilot car was non-compliant with the posted speed limit on about one-third of its trips, including an item in pre-work checklists would be beneficial to remind pilot car drivers to keep their speeds within posted limits. When following a speeding pilot car, motorists might be encouraged to speed both when a pilot car is in operation and when it is not. Therefore, improving compliance of pilot car has potential to help better improve compliance of all motorists.

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